Renewable and Sustainable Energy Reviews 13 (2009) 1985–1993

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

'From graft to bottle'—Analysis of energy use in viticulture and wine production and the potential for solar renewable technologies

M. Smyth [a,*], J. Russell [b,1]

[a] Centre for Sustainable Technologies, School of the Built Environment, University of Ulster, Newtownabbey BT37 0QB, Northern Ireland, UK
[b] Appalachian State University, Boone, NC 28608, USA

ARTICLE INFO

Article history:
Received 24 October 2008
Accepted 21 January 2009

Keywords:
Viticulture
Enology
Energy
Solar thermal
Photovoltaic

ABSTRACT

The practice of viticulture and winemaking is highly dependent upon the weather and climate. Any future changes in the seasons, their duration, local maximum, minimum and mean temperatures, frost occurrence and heat accumulation could have a major impact on the winegrowing areas of the world. Given that the winegrowing industry has substantial energy requirements and is directly influenced by any changes in climate, the industry should be at the forefront in promoting the case of energy efficiency and the adoption of renewable technologies. Solar renewables in the form of solar thermal and photovoltaics (PVs) offer a complimentary solution to many winegrowing processes. This paper examines the limited number of world wineries that have adopted solar renewables and presents a viable case for their wide scale integration into the industry.

The paper presents a range of viticultural and winemaking processes where solar energy can be directly or indirectly applied and suggests the potential for solar energy in making substantial savings in both energy use and greenhouse gas emissions. In 2005, almost 8 million hectares were under vines producing 40.2 million tonnes of grapes for crushing. The total global energy use within the winemaking industry is estimated at over 105 PJ emitting nearly 16 million tonnes of CO_2. If ancillary industries, such as bottle making and transportation are included, the total carbon footprint of the industry is estimated at over 76 million tonnes of CO_2. This paper calculates that if the commercial winemaking establishments in the 'developed' wine producing regions of the world integrated a 'small' solar installation into their wineries, the potential savings are 18.3% or 19.24 PJ of the energy used in the global winemaking industry.

Contents

* Corresponding author. Tel.: +353 2890368119; fax: +353 2890368239.
E-mail addresses: m.smyth1@ulster.ac.uk (M. Smyth), russellja@appstate.edu (J. Russell).
[1] Tel.: +1 828 262 7708.

1364-0321/$ – see front matter
doi:10.1016/j.rser.2009.01.007

1. Introduction to solar energy in winegrowing

Climate change and its potential impact is one of the greatest challenges facing mankind today. The practice of viticulture and winemaking is highly dependent upon the weather and climate. Any future changes in the seasons, their duration, local maximum, minimum and mean temperatures, frost occurrence and heat accumulation could have a major impact on the winegrowing areas of the world. These changes are already evident in the form of increased vineyard plantings in what were a number of years ago thought to be marginal regions, such as southern England, or the movement of 'traditionally warmer' varietals into new 'cooler' regions.

Winegrowing (viticulture and enology) is a global industry, representing a significant demand on the world's resources, including fossil fuels. In 2005, 7,876,000 ha (19,462,000 acres) were under vines [1] producing 286,175,000 hectolitres of wine equivalent to 3.816^{10} standard bottles [2]. It could be argued that winegrowing given its energy requirements and the detrimental effects that climate change may bring to the industry, should be at the forefront in promoting the case of energy efficiency and the adoption of renewable technologies. Solar renewables in the form of solar thermal and photovoltaics (PVs) offer a complimentary solution to many winegrowing processes.

Most of the world's wine producing regions are found within the temperate latitudes of 30° and 50° in both hemispheres with annual mean temperature ranges between 10 and 20 °C, constantly changing seasons with variable conditions and around 700 mm of rainfall throughout the year. In addition the requirement of 13:00–15:00 h of sunshine during the growing season implies that most wineries are located in regions were the solar resource is highly favourable. These factors and the multitude of buildings with suitable mounting surfaces and all-year-round energy demands indicate that any collected solar energy could be harnessed and put to best effect.

1.1. Viticulture

Solar energy already plays a very important part in the vineyard. The sun's energy is already necessary to produce the key ingredient; grapes. Of course while the input of the sun is taken for granted in the growing process, there are many processes during the viticultural stage where the energy from 'actively' collected solar energy could be utilised.

1.1.1. Site location

Good site selection usually means a good solar aspect. Generally equator facing slopes with little or no shading are preferred. However, the soil type, texture and water retention are often selected because of their solar collection ability. Many vineyards have very stony or have exposed outcroppings of equator facing rocks which will absorb heat from direct solar radiation during the day and release it at night, thereby improving the micro-climate (Fig. 1).

1.1.2. Preparation and planting

The process of site preparation and planting is mechanically intensive and requires significant energy input. In the year prior to planting, the ground may be sub-soiled, followed by ploughing and harrowing. There may also be a drainage requirement and fertility adjustments to the soil. These activities require input from large agricultural vehicles and mechanical equipment. Electrically powered farm utility vehicles are becoming very popular. In the vineyard the potential application of such vehicles is significant. They are quiet, nimble and have increased responsiveness and produce no localised pollution. Add to this the potential for photovoltaic charging, they could offset a significant portion of carbon emissions in the vineyard. Properly charged and maintained electric vehicles should be able to run for a full day carrying out a range of functions. However, the vehicles and mechanical equipment used in site preparation require significant horsepower and thus are wholly dependent upon fossil fuels. It is unlikely that solar energy in the form of photovoltaic powered vehicles could be of benefit in this application.

Fig. 1. Enhanced solar collection and storage using a stony site at the Waipara Valley Vineyard, Pegasus Bay, New Zealand.

Fig. 2. Tubex growtubes used in Ridgeview vineyard, Australia (reproduced by kind permission from TUBEX Ltd.).

Once a suitable layout has been determined the vines should be planted in a north/south row alignment, unless there are other contributing factors. Again the solar input is important as the north/south row alignment ensures an even solar distribution across the vine canopy in later years. Ground coverage in the form of polymer mulch mats, laid before planting to make the laying process easier, can have a significant effect on the soil and will immediately effect solar collection in the vineyard.

It is common practise to have a vine tutor along with the young plant, however, it is becoming more and more common that some form of grow tube is also utilised. The benefit of grow tubes is well documented, making full benefit of any incident solar radiation, creating a mini-greenhouse environment around the young plant, thus increasing growth and time to establishment (Fig. 2). An advancement of this concept is the use of polytunnels to improve establishment or increase solar collection and heating in locations were the climate for winegrowing is marginal (Fig. 3).

1.1.3. Establishment and training

The training of young vines in the first 2 years is critical to the future performance of the vineyard. Vines that do not establish well due to poor cultural management are usually set back several years. One goal is to establish a large healthy root system by promoting maximum amounts of healthy, well-exposed foliage. To accomplish this goal during the first 2 years, care must be taken to train vines properly and ensure a healthy growing environment. Grow tubes can provide this environment and promote rapid shoot growth early in the season, resulting in a single dominant shoot that has long internodes and is very straight. A trellis should be established soon after planting to provide the necessary continued support.

Fig. 3. Polytunnels used in a vineyard in Southern England.

Fig. 4. Spray application of herbicides in a vineyard in Southern England.

1.1.4. Pests and disease control

It is necessary to control soil borne pests in vineyards, particularly weeds. Weeds can compete for water and nutrients, thereby reducing vine growth, contaminate mechanically harvested fruit, provide alternate hosts for vineyard pests and interfere with vineyard operations. Weed growth can also alter the microclimate around vines, leading to a higher disease risk and increasing the threat posed by of spring frost. Pest control usually requires the application of herbicides and pesticides. The use of these materials is often undesirable due to their toxicity to animals and people, their residual toxicity in plants and soils, the complexity of soil treatment and their high cost. In addition, the regular spraying of the treatment is energy intensive and requires significant mechanisation in the form of vineyard vehicles spraying up and down the vine rows. PV electric powered vehicles may be an ideal substitute to conventionally fuelled vehicles (Fig. 4).

Soil solarisation is a novel application of solar collection that can reduce the need for regular spraying, thus cutting down energy use. Elmore et al. [3] conducted a study into the placing plastic sheets on moist soil during periods of high ambient temperature. The plastic sheets allow the sun's radiant energy to be trapped in the soil, heating the upper levels. Solarisation during the hot summer months can increase soil temperature to levels that kill many disease-causing organisms, nematodes and weed seeds and seedlings. Fig. 5 details the average air, surface and soil temperatures measured with and without plastic quilt sheeting. A significant difference in the bare soil temperature (−200) and the plastic quilt sheeting temperature (−200) is apparent. The respective surface temperatures (000) and air temperatures are also shown (+200).

Mammals and birds can present a significant problem in the vineyards. PV powered pest control systems are becoming popular and have a particular benefit in remote or extensive vineyard plantings. Small sonic scare units are typically powered through a 20 W PV module, continually charging a 12-V battery for normal operation.

1.1.5. Frost protection

Frost is an ever present danger to the vineyard owner, threatening to cause irreversible damage to fruit yields. Each year hundreds of thousands of hectares of vines are damaged by radiation frost events that occur during spring time (after 'bud burst') and during autumn (before harvest). From a study conducted by Smyth and Skates [4], it is estimated in the 14 most

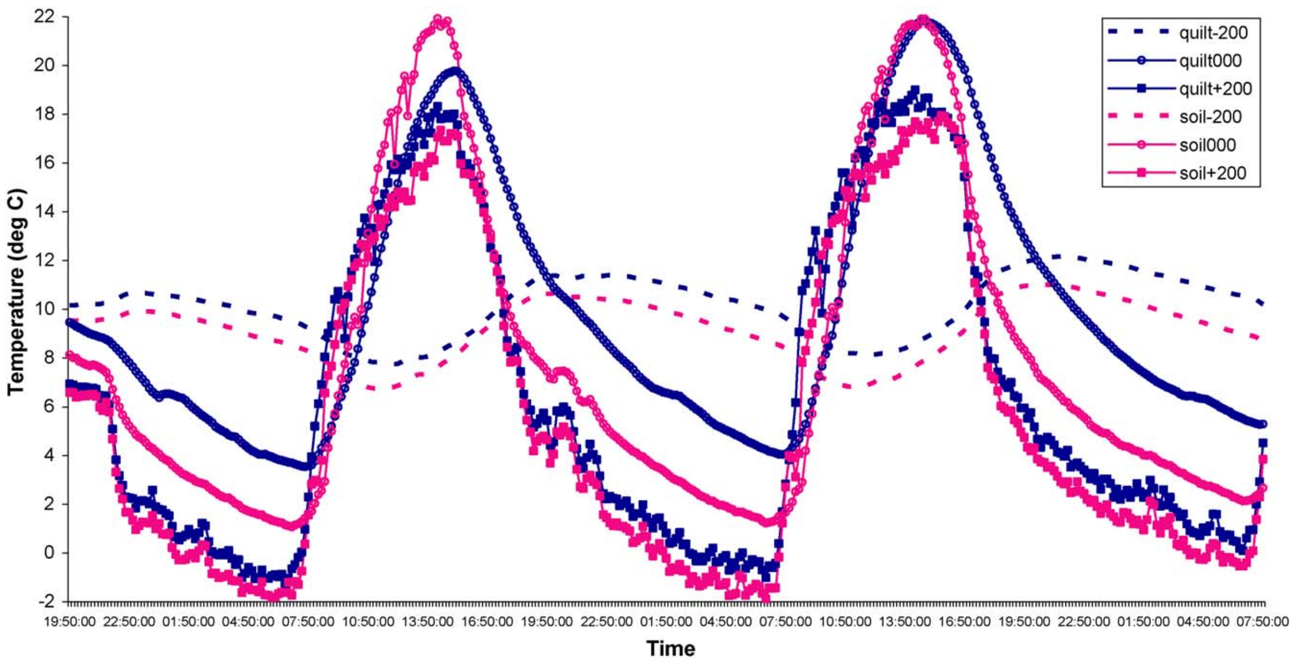

Fig. 5. Average air, surface and soil temperatures measured at the Waihopai Valley Road vineyard, New Zealand with and without plastic quilt sheeting [4].

important wine producing regions of the world approximately 1,776,150 ha are susceptible to spring frost events. To minimise the risk, in addition to good site selection and vineyard management, a number of active frost protection systems are available. Most active methods of frost protection are costly in monetary terms and can also have a detrimental effect on the environment. Fig. 6 illustrates the lengths that worried wine growers will go to in the protection of pre-bud-burst vines to frost events. The image shows a diesel powered wind mill which is a common, yet energy intensive method of moving warmer air into the vineyard.

Passive solar frost protection relies on the ground absorbing, storing and releasing sufficient solar energy to raise temperatures above freezing during conditions that would normally result in a frost. During critical spring and autumn periods there is more than enough daytime solar energy available to reduce this night time drop in temperature if only the energy could be collected and stored. Many vineyard soils, however, are incapable of storing sufficient solar energy (Fig. 7).

Ground coverage directly below the vine trellis has a significant effect on thermal absorption and heat storage of the soil [5]. As with Elmore et al. [3] study, solarisation with plastic mulch can be used to increase relative soil temperatures and thus provide some level of improved frost protection. Smyth and Skates [6] investigated a specifically designed solar water heating quilt that mimics the mulching effect of black plastic systems, but crucially, due to the water filled cavity, provides a significant improvement on bare soil conditions or single sheet mulching by virtue of its thermal mass and improved contact profile with the ground below. The study indicated that the solar quilt could give a 38.5% improvement in heat collection resulting in 32% more heat being released during the night when compared to bare soil conditions.

1.1.6. Fertilizing

Vineyard fertilization practices aim to improve the supply of available soil nutrients to the levels required for optimum grapevine growth and yield. Most soils will contain the adequate amount of essential nutrients, but is normal to introduce a

Fig. 6. Diesel powered wind mill for frost protection at the Gladstone vineyard, Martinborough, New Zealand.

Fig. 7. The solar water heating quilt in field trials [6].

Fig. 8. Reflective white mulching mat used at the Gladstone vineyard, Martinborough, New Zealand.

management program to complement the soil's ability to provide the nutrients needed to sustain adequate vigour and produce the desired quantity and quality of crop. There are a wide variety of means in applying fertilisers, composts and manures, all which requires mechanisation. As in pest and disease control methods, PV electric powered vehicles may be an ideal substitute to conventionally fuelled vehicles in carrying out these processes.

1.1.7. Irrigation

In the 'Old World' vineyards of Europe irrigation is normally not used, with vineyards relying on natural precipitation to meet water demand. However, in the 'New World', irrigation is viewed as essential and drip irrigation has become standard practice. Almost all irrigation systems rely on some form of pumping. In most situations, the use of photovoltaic (PV) powered pumping stations is ideal, with good matching of demand/supply characteristics. PV pumping can also be used indirectly to pump water into a head tank for irrigation at an offset time when the peak solar resource is not available.

1.1.8. Canopy management

Canopy management is a term used to describe both proactive and remedial measures taken to improve vine canopy characteristics, and is defined by the shoot system of the vine, including stems, leaves and fruit. The climate within the canopy is referred to as the canopy microclimate and amongst other variables, access to sunlight is paramount. The general consensus is that a maximum area of leaves and fruit should be exposed to solar radiation.

Although good design and maintenance of the canopy (spacing, height, hedging, etc.) should be practised, the use of solar ground reflectors has been investigated and has been shown to increase vegetative growth and yield by selecting an appropriate reflective foil [7]. In addition to a reduction in soil evaporation and the prevention of weed emergence, the application of coloured plastic foils as a mulching material appears to alter the microclimatic conditions of the vineyard (Fig. 8).

1.1.9. Harvesting

Ripe grapes are harvested either by hand or by mechanical harvesters; the method of collection is very dependent upon the quality and added cost value of the finished wine. Mechanical harvesters straddle grapevine trellises and, using firm plastic or rubber rods, strike the fruiting zone of the grapevine to dislodge the grapes and transfer them directly to storage. Although mechanical harvesters require more energy input, hand gathered grapes must still be conveyed from the vineyard to the winery. PV electric powered vehicles are a suitable replacement to conventionally fuelled vehicles in carrying out these journeys.

1.1.10. General upkeep and maintenance

The general upkeep and maintenance of a vineyard can be resource intensive, both in labour and energy. They may include tasks, such as grass cutting, row grubbing and boundary fencing and trellis maintenance. These are all tasks that could easily be augmented through the use of solar powered vehicles and tools. Weather monitoring stations may also represent a task where solar can be applied, particularly in remote locations.

1.2. Oenology

A number of studies have investigated the use of energy in the wine making industry, in particular, the use of energy in enology. Galitsky et al. [8] provide a detailed account of energy use and benchmarking from crushing to bottling (in the winery) for winemaking in California. In many wineries, the art of producing quality wines in quantity has become an industrialised process, and as such requires energy in many forms; heating, cooling, power, compressed gases, etc. All these requirements can be easily substituted via solar capture. In addition, winemaking is conducted in internal controlled environments and thus the general requirements of the building, such as thermal comfort, ventilation, lighting, power, sanitation and communication must also be satisfied.

1.2.1. De-stalking

Following harvest all suitable grapes, at the winery entrance, are weighed, inspected and unloaded into a hopper. At this stage it is necessary to remove all unwanted vegetative material from the grapes and thus a number of mechanical devices, such as screw conveyors are used to de-stem the grapes. Most de-stemming equipment is electrical, with a substantial percentage relying on compressed air indirectly powered by electricity. Other energy needs include cooling, water supply and pumping needs. The de-stalked grapes are then sent to be crushed.

1.2.2. Crushing

Crushing involves a general squeezing of the grapes to produce a liquid mixture that contains the grape juice and pomace (skins, seeds and pulp), otherwise referred to as the 'must'. Crushing equipment, as the de-stalking equipment is directly or indirectly electrically powered and like de-stalking may require other energy input for cooling, water supply and pumping needs.

1.2.3. Pressing

After the crushing process, the must is transferred to the pressing stage. Pressing is the act of applying pressure to grapes or pomace in order to separate juice or wine from grapes and grape skins. Pressing is not always a necessary act in winemaking as a certain amount free-run juice can liberated at crushing. However, most wineries opt for a greater quantity of juice and thus pressing is necessary.

Historically, hand (or foot) crushing of grapes in open tanks or simple wooden basket presses using a ratcheting threaded screw system were common, requiring very little external power. Modern presses follow a rigorous pressing program, typically up to 2.0 bar, as duration and level of pressure can affect the quality of the wine. The membrane press is the most common form of press as it produces a better quality juice. Most systems are electrical, using motors, pumps and compressors and thus readily lends itself to solar electric supply.

1.2.4. Primary fermentation

Fermentation is the key stage in the wine making process, producing the distinctive characters of the wine. In most wineries the process of converting the natural sugars in the grape juice to alcohol and carbon dioxide by yeasts is typically done in stainless steel vessels, although wooden vats or barrels may also be used. Temperature is very important during this stage cooling (and sometimes heating) may be required, representing a significant energy input. Fermentation continues until the required wine character has developed.

Due to the large cooling load electrical refrigeration plant based on the vapour compression cycle is the most commonly used method in producing the chilled water necessary in the cooling circuits. However, several studies have highlighted the benefit of using solar absorption refrigeration and the benefits of direct load/supply matching. High temperature evacuated solar heat pipes supply the generator of a lithium-bromide absorption refrigeration plant with heat to indirectly provide the cooling effect. Conversely, should heating be required, this can be supplied directly to the process.

1.2.5. Clarification

Once primary fermentation is complete, the vast majority of the suspended solids have been separated from wine by sedimentation (fining may be included at this stage). The wine can then be clarified from the spent yeasts and other solids (lees) to produce a clear wine. The most common clarification techniques are racking, centrifugation, filtration and electro-dialysis. Racking is the slowest process, but has a low energy intensity, while the others are faster but have higher energy requirements. Racking may also be used to improve stabilisation. Both solar thermal and photovoltaic systems have potential for this process.

1.2.6. Storage and secondary fermentation

The wine is generally stored for a period of time after clarification. Depending on the wine and winery, the wine can be stored in large tanks or in smaller wooden barrels. During this time the wine is aged and may be subject to secondary fermentation. The time of storage is dependent upon the wine but all levels of storage require a certain level of climate control. This may be achieved through mechanical means or via passive measures, such as free cooling via purging or thermal mass as in underground storage.

1.2.7. Bottling

Once the finished wine has been produced, the wine is bottled, either on-site or out-sourced. Bottling can be a simple gravity fed process with manual labelling and corking right through to a highly automated bottling line. There may be a need for further filtering and ensuring sterile conditions is of the utmost importance.

1.2.8. Bottle storage

The finished bottles are then stored prior to selling and/or transportation. To maintain the wine quality bottles are usually stored at a lower temperature. This may be achieved through mechanical means or via passive measures, such as free cooling via purging or thermal mass as in underground storage.

1.2.9. Other processes

In addition to the processes involved in oenology mentioned previously, significant amounts of energy is expended in ancillary processes, such as washing and cleaning, transportation via conveyers, pipelines and forklifts and waste disposal of waste-water, pomace and lees, requiring collection, treatment and disposal. Solar energy can be used quite easily to augment these processes; solar thermal for steam or hot water production in cleaning processes and solar electric power for pumping and conveyance or charging forklift batteries. Solar radiation can also treat vineyard/winery wastewater while photovoltaic powered pumps have been used to move or agitate wastewater ponds.

Table 1
Total estimated energy requirement for the global winemaking industry in 2005.

Category	Winemaking (GJ)	Vineyard (GJ)	Winery (GJ)
Electricity	35,782,820	13,851,850	21,930,970
Stationary	10,524,360	1,900	10,522,460
Site transport	58,936,420	28,878,850	30,057,570
Total	105,243,600	42,732,600	62,511,000

1.3. Global energy use in winemaking

The energy expended in the global production of wine is enormous. In 2005 almost 7,876,000 ha were under vines [1] producing 66 million tonnes of grapes, of which 40.2 million tonnes were crushed for wine production [9], producing over 286 million hectolitres of wine [2]. The vast majority of the winemaking produce was carried out on an industrial scale in the ‘developed’ or ‘near-developed’ regions of the world. In a study reported by Jones [10] it was determined that 2.618 GJ of energy was required in the processing of 1 tonne of grapes into a final product; 1.063 GJ/tonnes in the vineyard and 1.555 GJ/tonnes in the winery. Based on these values, the total energy requirement for the global winemaking industry (excluding bottle making and final product transport) can be estimated and the outcome is presented in Table 1.

Energy use within the winemaking industry is presented in three basic formats; electricity, stationary fuels and site transport fuels. The combined total of over 105 PJ represents a significant energy requirement, enough to supply all the space heating and hot water needs for 1.67 million households in the UK for a year. Site transport fuels contribute the most at just under 59 PJ, spilt almost evenly between the vineyard and winery, consisting of petrol, diesel and small amounts of LPG. Stationary fuel use is almost exclusively winery based. Almost 10.5 PJ in the form of oils, LPG and natural gas are combusted directly on-site to produce hot water and indirect electrical production. The small vineyard consumption is in part used it remote stand-alone units for frost protection. Over 60% of the 35.8 PJ of electricity is used in the winery, with a large percentage of the electricity used in the vineyard used in pumping processes. Apart from the ‘traditional’ requirements of electricity (comfort, lighting, general power, etc.) in the vineyard buildings, much of the electricity used in winemaking is needed in refrigeration plant for cooling and storage, compressed air, hot water production, pumping and mechanical process equipment and lines.

The global cost of these processes at 153 kg CO_2/tonne and 235 kg CO_2/tonne [10] for the vineyard and winery respectively for the examined year of 2005 is 15.6 million tonnes of CO_2. The energy used in vineyards contributes 6,150,600 tonnes of CO_2 while the energy used in the winery contributes 9,447,000 tonnes of CO_2. This is an average of 0.41 kg of CO_2 per standard bottle produced. However, taking into account bottle manufacturing and transportation it has be estimated by Colman and Päster [11] that the total carbon footprint could be an average of 2 kg of carbon per standard bottle resulting in a total carbon footprint for the industry of 76.3 million tonnes of CO_2.

1.4. Solar energy in winemaking

The use of solar energy in the winemaking industry is not a new concept; one could say it has been the major energy input for years.

However, in the last few decades the industry has become highly mechanised and reliant on fossil fuels. Because of the concerns throughout the world, many of the winemaking governing bodies around the world are aware of the benefits in adopting solar energy. The savings are not just environmentally sound but can yield significant economic benefits, not to mention the positive image portrayed by installing solar systems. Smith [12] reports that an analysis of the French Champagne industry could reduce emissions by 20–30% using solar energy over the next 10 years without serious technical disruption. The application of solar energy is technically viable and it is only sensible that there should be wide scale application of solar renewables.

The size of individual vineyards in the world is different. In the Old World, Europe's 1.594 million vineyards (holdings) are an average of 2.13 ha each, while the average New World vineyard is 50 ha, providing considerable economies of scale [9]. The EU represents almost 45% of the world's vineyard coverage with almost 3.5 million hectares while the recognised New World producers cover almost 1.2 million hectares in just over 23,500 vineyards. However, the bulk of the vineyards in the Old World are owned by 'small farms' and holdings growing grapes for wine are in general small. More than 71% have less than 5 ha, while more than 12% range from 5 to 10 ha, leaving 17%, or 270,980, commercially viable vineyards [9].

If we combine the recognised New and Old World winegrowers, representing the most developed wine producing nations, there is an estimated 184,300 (New World, 23,500 + Europe, 160,800 [9]) establishments that could economically utilise solar energy (based on regions with up-to-date viticultural and oenological techniques). Of this number very few are actually making use of this resource. Some examples of solar thermal and photovoltaic installations are discussed below.

1.4.1. Old World

On the face of it relatively few Old World vineyards have adopted solar renewables, although there are some notable exceptions.

The Alois Lageder vineyard/winery in Bolzano, Italy promotes the use of solar thermal and PVs, including good passive design features in its winery. The winery has 24 m^2 of solar collectors with storage and has been reported to supply the winery with all the hot water it needs. In addition, 160 PV modules (136 m^2) are mounted on the winery roof at 30° facing south-southeast at 17.7 kWp (Fig. 9).

Fig. 9. Solar installation at Alois Lageder (reproduced by kind permission from Alois Lageder).

Fig. 10. Photovoltaic system at Fetzer's administrative building (reproduced by kind permission from Brown-Forman Corporation).

At Cortes de Cima, Alentejo, Portugal, a 56 m^2 south facing solar array combined with a 5000 l storage tank can supply the winery with all its hot water needs. The Achaia Clauss Winery in Patras Greece has 300 m^2 solar water heating system installed on the winery roof (with 10 m^3 storage), supplying an average of 1.62 MJ per day.

1.4.2. New World

The New World, whether due to its larger vineyards or modern winemaking approach has been more open to the concept of adopting solar renewables, with many installing both solar water heating systems and photovoltaics. California seems to be particularly advanced in the integration of solar installations, both passive and active.

The Stanly Ranch winery in the Napa Valley has a 277 kWp photovoltaic system. It is estimated that the PV system will provide 90–100% of the winery's annual electricity requirement. Green & Red Vineyard, St. Helena's California has powered all their irrigation pumps with PVs. Mount Eden Vineyards in Saratoga, California has a 20 kW photovoltaic system comprising 136 panels. Vino Noceto Winery in Plymouth California has a 10 kWp PV system, consisting four 2.5 kW panels mounted on the winery building facing southwest at a slope of 15°. California's Fetzer Vineyards produces a significant portion of the electricity for its administrative building through a 41 kWp PV system. The company has also committed to installing a 899 kWp photovoltaic system at Fetzer's Hopland winery, producing 1.1 million kWh annually, supplying 80% of the bottling plant's electricity needs (Fig. 10).

The most impressive application of solar renewables to date has been that of the EOS Estate Winery in Paso Robles, California which is planning to be the largest winery in California's Central Coast to run completely on alternative energy. The solar installation proposed uses two acres of ground-mounted tracking solar PV modules, totalling 3084 modules giving 540 kWp, providing all of the electrical power needs for the winery and tasting room. In addition, 60 roof-mounted solar thermal collectors will provide all the hot water needs.

Shafer Vineyards in California was the first winery in Napa and Sonoma counties to convert to 100% solar power. The array is made up of 784 PV panels producing 129 kWh (under peak solar conditions). The installation is quite unusual in that, rather than being exclusively mounted towards the equator; the Shafer installation consists of two east facing arrays, which provide power for Shafer's visitor and administrative areas and two west and two south facing arrays providing power for the winery, cellar and wine cave. The vineyard is currently building a new south-

Fig. 11. Photovoltaic system at the Shafer vineyard winery (reproduced by kind permission from Shafer Vineyards).

Fig. 12. Photovoltaic system at Sokol Blosser Winery (reproduced by kind permission from Sokol Blosser, photo by Doreen L. Wynja).

facing array to generate additional energy to power the water reclamation pond and drip irrigation system (Fig. 11).

In the Willamette Valley, Oregon, a 23.8 kWp PV system produces about one-third of the Sokol Blosser winery's electricity needs. The panels were installed at the top of one of the estate vineyard blocks in December 2006 (Fig. 12).

The Fermoy Estate, Margaret River, Australia has three Solarhart units with gas boosting, producing 1000 l perday of water at 88 °C, producing all the hot water we needed for the winery. Smith [12] in a desktop study of water use by Ferngrove Winery in the Frankland River region, Australia reports that the winery needed 5000–10,000 l of water per day at 90 °C. Eight solar collectors rated at 10 kW, could yield an annual saving in carbon dioxide emissions of 26 tonnes.

1.5. Potential solar savings in winemaking

According to the DGS [13], a solar water heating system located in a region broadly banded in the wine producing areas of the world, should yield between 400 and 650 kWh/m^2/year (1.44 and 2.34 GJ/m^2/year). The yearly solar electricity generated by a 1 kWp system with optimally inclined modules and performance ratio of 0.75 located in a region broadly banded in the wine producing areas of the world, should produce between 1050 and 1500 kWh/kWp (3.78 and 5.4 GJ/kWp).

Using conservative estimates and solar water heating systems covering 20 m^2 and PV systems rated at 20 kWp, all 184,300 winemaking establishments in the 'developed' wine producing regions of the world could save 18.3% or 19.24 PJ of the energy used in the global winemaking industry. This can be summarised as follows:Employing 20 m^2 solar water heaters yields 5,308,000 GJ per year ($20 \times 1.44 \times 184{,}300$) or 50.4% of the estimated 10,522,460 GJ of stationary fuel use, primarily in hot water production in the winery.Employing 20 kWp PV arrays yields approximately 13,933,000 GJ per year ($20 \times 3.78 \times 184{,}300$) or 63.5% of the estimated 21,930,970 GJ of the electricity use in the winery and vineyard.

Of course, these values are based upon quite small installations (given the example vineyards presented in this paper) and thus may be conservative, representing quite a small investment, particularly to larger producers. In practise, larger systems may be installed to meet a greater portion of the winery load and therefore the solar contribution would be seen to be higher.

These options are explored briefly below in 5 scenarios. The scenarios range from the industry offsetting all of its estimated carbon emissions (both including and excluding bottle manufacture and transportation to the final customer) and also the use of solar energy to offset each of the three main onsite energy usage categories (electricity, stationary fuels, and onsite transport fuels). Each of the scenarios below uses the following assumptions:

- average daily full sun of 4 h [13];
- average solar PV system efficiency of 12% (area calculations only);
- average solar thermal system efficiency of 60% (area calculations only);
- levelized cost of solar hot water of \$0.08 per kWh thermal [14];
- levelized cost of solar PV (industrial scale $\geq$500 kWp) of \$0.214 for the US [15] and €0.20 for the EU [16];
- levelized cost of solar PV (commercial scale $\geq$50 kWp) of \$0.274 for the US [15] and €0.28 for the EU [16];
- levelized cost of solar PV (residential scale $\geq$2 kWp) of \$0.378 for the US [15] and €0.42 for the EU [16];
- average carbon intensity of electricity of 1.1 kg CO_2/kWh [10];
- average carbon intensity of stationary fuels of 0.193 kg CO_2/kWh [10];
- average carbon intensity of transport fuels of 0.25 kg CO_2/kWh [10].

1.5.1. Scenario 1: offset all carbon emissions (including bottle manufacture and transport)

While it is likely that individual business sectors will be required to address their carbon emissions worldwide through a global carbon trading scheme, it does not seem likely that the winemaking industry would be held accountable for the emissions of suppliers namely the bottle manufacturing sector and the transportation sector. Therefore, this scenario is given as a worst case to estimate the cost to the wine industry of addressing all of the carbon embodied in their product by the time it reaches the consumer. Assuming average CO_2 emissions of 2 kg per bottle including bottle manufacturing and final transportation [11], a peak capacity of 47.5 million kW installed solar PV would be required to offset the annual carbon emissions of 76.3 million tonnes of CO_2. This PV array would generate 69.4 billion kWh per year and would occupy 38,000 ha or 0.48% of the land devoted to wine making currently. The levelized cost per bottle not including the cost savings from the sale of the electricity produced is estimated at €0.366 (\$0.389), €0.512 (\$0.499) and €0.764 (\$0.687) for industrial, commercial, and residential scale PV installations respectively. While this is quite expensive, this scenario allows an entire industry to become completely carbon neutral practically overnight with existing technology.

1.5.2. Scenario 2: offset all carbon emissions (excluding bottling and transport)

This scenario provides a more realistic estimation of the implementation of both solar PV and solar thermal power to

eliminate or offset all of the carbon emissions over which the industry has direct control. Solar thermal power is used to replace all stationary fuel usage (it is assumed that all stationary fuels are consumed to produce heat), while solar PV is used to replace electricity and offset the emissions from on site transport fuels. Combining all three fuel categories requires a total annual solar generation of 16 billion kWh. These combined solar PV and solar thermal systems would require 7770 ha of land or 0.1% of the land devoted to wine making currently. The levelized cost per bottle not including the cost savings realized from not purchasing the electricity and fossil fuels is estimated at €0.077 ($0.082), €0.106 ($0.103) and €0.156 ($0.141) for industrial, commercial, and residential scale PV installations respectively. With more detailed information regarding utility rates and actual consumption for individual wineries, better estimates can be generated. Once discounts for utility purchases are included this could be an attractive scenario. This scenario would eliminate the generation of 15.6 million tonnes of CO_2.

1.5.3. Scenario 3: replace all electricity with solar PV

The winemaking industry consumes an estimated 9.95 billion kWh of electricity per year. Installing solar PV with a peak capacity of 6.82 million kW would meet current consumption. This PV array would occupy 5450 ha or 0.07% of the land devoted to wine making currently. The levelized cost per bottle not including the savings from not purchasing grid power is estimated at €0.052 ($0.056), €0.073 ($0.072) and €0.110 ($0.099) for industrial, commercial, and residential scale PV installations respectively. This scenario would eliminate the generation of 10.9 million tonnes of CO_2.

1.5.4. Scenario 4: replace all stationary fuel with solar thermal

The winemaking industry consumes and estimated 2.92 billion kWh of fuels for stationary applications per year. Assuming that the stationary fuels are used exclusively to produce heat, installing solar thermal collectors with a peak capacity of 1.6 million kW would meet current consumption. This solar thermal array would occupy 266 ha or 0.003% of the land devoted to wine making currently. The levelized cost per bottle not including the savings from not purchasing the fossil fuels is estimated at €0.005 ($0.005). With 563,000 tonnes of CO_2 avoided, this is a very attractive scenario.

1.5.5. Scenario 5: offset site transportation fuel emissions with solar PV

While it will become more feasible in the near future to replace fossil fuelled vehicle with battery electric vehicles due to the rapid improvement of battery technologies, this scenario does not replace but offsets the emissions from fossil fuel burning vehicles. The winemaking industry consumes an estimated 16.5 billion kWh of transport fuels per year. Installing solar PV with a peak capacity of 2.57 million kW would be required to offset the annual carbon emissions. This PV array would occupy 2060 ha or 0.03% of the land devoted to wine making currently. The levelized cost per bottle not including the market value for the power is estimated at €0.020 ($0.021), €0.028 ($0.027) and €0.041 ($0.037) for industrial, commercial, and residential scale PV installations respectively.

While these are ambitious scenarios, they do not take into account the myriad of other potential applications of solar energy in the industry, such as soil solarisation to replace agri-chemicals, primary solar thermal refrigeration, 'waste' solar thermal used to offset electrical requirements for refrigeration if it is applied using absorption refrigeration, passive building design, and the many other possibilities. In addition, solar energy can be used in the vineyard to actively produce power for electric vehicles or passively to offset fossil fuel use in frost protection actions. It is these later areas that will form the basis for future investigation and analysis.

2. Conclusions

The winemaking industry is highly dependent upon the weather and climate and with the world facing substantial changes in climate and energy use, the industry must develop and embrace the potential for active solar capture and utilisation. Solar renewables in the form of solar thermal and photovoltaics (PVs) have been shown to offer a range of complimentary solutions to many winegrowing processes.

Of the 7,876,000 ha in 2005 under vines, producing 40.2 million tonnes directly for wine, there is an estimated 105 PJ of energy used representing 15,597,600 tonnes of CO_2. If an estimated 184,300 commercial winemaking establishments recognised in the New and Old World were to install a 'small' solar installation into their wineries, the potential savings could be 18.3% or 19.24 PJ of the energy used in the global winemaking industry. If the larger winemaking establishments choose to install industrial scale ($\geq$500 kWp) solar PV systems with complimentary solar water heating systems, the cost of eliminating all direct industry carbon emissions could be as low as €0.077 per bottle.

References

[1] Anon. World vineyard acreage by country. San Francisco, California, USA: The Wine Institute; 2006.
[2] Anon. World wine production by country. San Francisco, California, USA: The Wine Institute; 2006.
[3] Elmore CL, Stapleton JJ, Bell CE, DeVay JE. Soil solarization—a nonpesticidal method for controlling diseases, nematodes, and weeds. In: California agriculture, vol. 51. Oakland, California, USA: University of California, Division of Agriculture and Natural Resources; 1997.
[4] Smyth M, Skates H. Vineyard frost protection and environmental management system. INI compete phase 1 detailed feasibility study report. Belfast, UK; 2003.
[5] Snelgar WP, Richardson AC, Paul HR, Lupton GP. Influence of soil mulching on winter chilling of kiwifruit. New Zealand Journal of Crop and Horticultural Science 1999;27:125–32.
[6] Smyth M, Skates H. A passive solar water heating system for vineyard frost protection. In: Proceeding of renewable energy in Maritime Island climates; 2006.p. 351–7.
[7] Bunty S, Rana R. Coloured plastic mulches on horticulture crops. India: Science Tech Entrepreneur; 2005.
[8] Galitsky C, Radspieler A, Worrell E, Healy P, Zechiel S. Benchmarking and self-assessment in the wine industry. In: Proceedings of ACEEE summer study on energy efficiency in industry; 2005. p. 436–47.
[9] Anon. WINE—economy of the sector. EU: European Commission, Directorate-General for Agriculture and Rural Development; 2006.
[10] Jones K. Australian wine industry. State of the environment 2003. Australia: South Australian Wine Industry Association Incorporated; 2004.
[11] Colman T, Päster P. Red, white, and "Green": the cost of carbon in the global wine trade. New York, USA: American Association of Wine Economists (AAWE) Working Paper No. 9; 2007.
[12] Smith F. Wineries of the future, cutting energy use. The Australian & New Zealand Grapegrower and Winemaker, No. 497; 2005.
[13] DGS (The German Solar Energy Society). Planning and installing solar thermal systems: a guide to installers, architects and engineers. London, UK: James and James Ltd.; 2005.
[14] Northwest Power & Conservation Council (NW Council). Solar energy systems for the million solar roofs initiative, document 98-19. Oregon, USA; 1998.
[15] Solar Buzz. Solar electricity global benchmark price indices: September 2008 survey results, www.solarbuzz.com; 2008 [accessed September, 2008].
[16] Diamantaras K. The prospects for renewables in the EU. Brussels, Belgium: ICCF Workshop; 2005.